PROSPECTS FOR HYDROGEN FUELED VEHICLES

Roger J. Schoeppel

Oklahoma State University
Stillwater, Oklahoma

Modern civilization is generally said to be a consequence of the industrial revolution; a striking outward manifestation of which is the automotive vehicle. Whereas the transition from animal to mechanical means of propulsion was accompanied by an increased mobility, this transition has not occurred without some accompanying undesirable side effects. One of these, environmental pollution, is now globally recognized and presents a real challenge for its solution. Another, an impending energy crisis, is due to the insatiable appetite for energy brought about by an expanding population and a rising affluence. The two are correlative since pollution is largely attributed to an apathy for the consequences of large-scale consumption of certain forms of energy.

Some recent developments in internal combustion engine technology may have provided not only a viable solution to the environmental-energy dilemma but also a convenient mechanism for transforming to a less polluting society. The development involves a novel method of designing internal combustion engines so they can smoothly and efficiently operate on hydrogen. The purpose of this paper is to review the opportunity offered by this capability and to forecast its probably future influence. The discussion will primarily be concerned with the use of hydrogen in ground vehicles although it is obvious hydrogen can be substituted for any other fuel now in use.

Prior Work

Early attempts to use hydrogen as a fuel in internal combustion engines were reported by Cecil in 1820[1] and by Barsanta and Matteucci in 1854.[2] However, the first significant contribution to the field waited until 1933 when Erren designed and built several engines which could operate on either hydrogen, conventional fuel, or their mixture.[1,3] His major problem and one that he was unable to overcome was detonation of the hydrogen-air mixture upon ignition.

After World War II, King and associates at the University of Toronto performed an extensive study using hydrogen as an engine fuel.[4] They found, as did Erren, that detonation was a formidable problem which could only be overcome by painstaking cleaning of the combustion chamber at least every 12 hours of operation. Apparently, these discouraging results had reduced interest in developing a carbureted air-breathing hydrogen fueled reciprocating engine.

An effort was initiated at Oklahoma State University in 1968 to try to design around the problems of pre-ignition and detonation which had troubled earlier workers.[5] The design approach selected was direct cylinder injection of gaseous hydrogen in a manner similar to fuel injection in a diesel engine.[6] This effort has resulted in the satisfactory conversion to hydrogen of four different engines originally designed to run on gasoline. Experience with these engines including extensive performance and emissions tests with one of them has yielded the following information:[7-10]

1. With reference to a gasoline engine converted to run on hydrogen, it is possible to "drive" a hydrogen engine to a higher horsepower output than was possible with gasoline fuel before its conversion.

2. The only undesirable emissions of significant concentration from a hydrogen engine are oxides of nitrogen (NOX). These were found to vary with operating conditions but averaged about 2.0 grams NOX per brake horsepower-hour. This rate of NOX production is about ten times less than from its gasoline counterpart.

3. The hydrogen engine can operate smoothly with compression, glow or spark ignition. With spark ignition, it can be idled down to about one-half the minimum idle speed possible with gasoline fuel.

4. The hydrogen engine is easy to start, responds rapidly to different rates of fuel injection, and runs cooler under low to intermediate loads than its gasoline equivalent.

From the foregoing, it is concluded that an automobile properly designed to run on hydrogen should be able to meet the 1975/76 federal emission standards.

Basis for Forecast

This section attempts to assess some techno-economic factors and political circumstances which may influence the future pattern of automotive vehicle development. Also included in the assessment are environmental and energy resource management considerations. This is the basis for the technological forecast which is made in partial response to the challenge presented by the 1969 U.S. Senate report:[11] The Search for a Low Emission Vehicle.

Environmental Constraints

There are many instances of pollution associated with normal and accidental activities of drilling, producing, transporting, refining, distributing, and consuming conventional hydrocarbon fuels. Collectively these contribute considerably to environmental decay. Industry can and will clean itself up but must be permitted to pass such costs on to the consumer. An alternate approach is to use hydrogen fuel produced by electrolysis of water. Although such a solution would require a long-term effort, it would appear to cause less pollution overall. Of immediate significance to this alternative are the motor vehicle emissions standards prescribed by the Clean Air Act as amended. These require that automobiles achieve a 90 percent reduction from 1970 emissions levels of carbon monoxide and hydrocarbons by the 1975 model year and a 90 percent reduction from 1971 emissions of nitrogen oxides for the 1976 model year. Prescribed standards for new light-duty motor vehicles for 1973 and successive years are as follows:[12]

Federal Standards for Composite Emissions from Light-Duty Vehicles on a Driving Cycle, grams/mile

Model Year	Hydrocarbons	Carbon monoxide	Oxides of Nitrogen
1973	3.4 (3.0)*	39.0 (28.0)*	3.0 (3.1)*
1974	3.4 (3.0)*	39.0 (28.0)*	3.0 (3.1)*
1975	0.41	3.4	3.0
1976 and later	0.41	3.4	0.4

*Numbers in parenthesis represent standards being considered for adoption

It is significant to note that by 1976, any vehicle covered by these specifications will be permitted to emit 0.41 grams of hydrocarbons, 3.4 grams of carbon monoxide, and 0.4 grams of nitrogen oxides per mile of a typical 7.5 mile driving cycle. Thus, whether one additional person is carried in a 2-passenger vehicle, or many in a 9-passenger one, each vehicle will only be permitted to emit so much pollution to the atmosphere. Also, since large engines emit more pollutants than do smaller ones, and unless some other provisions are made, the enforcement of these regulations will cause the disappearance of vehicles with large engines. Associated automobile comforts of space, air conditioning, power equipment, safety, acceleration and speed may also have to be sacrificed. In contrast, these changes may not be necessary with hydrogen fuel.

It also appears as if the automobile industry may be unable to meet the required 1976 federal emissions standards at a cost that can reasonably be passed on to the consumer unless;

a) the allowable pollution level is relaxed for one or more of the controlled emittants or

b) a federal subsidy or equivalent is enacted to support a portion of the costs.

In this connection, it appears worth mentioning that sufficient technology now exists to enable the design of a reliable engine that could meet the 1976 emissions standards. The technology does not exist, however, to be able to accomplish this objective at a reasonable cost. Hence, the problem is purely one of relative economics. In this regard it will be interesting to learn of the recommendations to the EPA of the Motor Vehicle Emissions Committee of the National Academy of Sciences who have recently been charged with determining whether the automobile industry is technologically capable of designing and mass-producing a reliable engine that can meet the federal motor vehicle emissions standards.[13]

Energy Management

The dilemma between environmental pollution and an abundance of low-cost energy is one that will have to be resolved by the public--provided it is offered the alternative. Unfortunately, however, this antithesis can not be resolved until an abundance of energy, or at least an abundance in the form that is desired, becomes available. Since energy is the key to survival of our society, its adequacy must be insured before stringent pollution regulations can be enforced. Accordingly, a permanent solution to the air-pollution-from-vehicles-problem can only be solved from a total energy management point of view. One such proposal is to create a Total Energy Management System (TEMS) in which hydrogen becomes the basic energy fuel.[14] The system proposed provides for the optimum management of our energy resources so as to place a minimum strain on the delicate ecological balance of the environment. This concept was expanded by proposing a Total World Energy Management System (TWEMS) with its primary function being to optimize energy utilization worldwide while simultaneously attempting to minimize pollution.[15] The creation of national and international "Energy Institutes" with similar such objectives is currently being considered at the United Nations sponsored Human Environment Conference.[16]

Substitutability

Hydrogen is substitutable with any other mineral fuel currently available. Its use has already been demonstrated in reciprocating internal combustion engines and turbines. Adaptation to external combustion engines is even simpler. For energy conversion via fuel cells the technology in this area is further advanced for hydrogen than any other fuel. Its importance in air travel is shown by a companion paper at this conference proposing to use liquid hydrogen in hypersonic transport.[17] Finally, the roles hydrogen could play in substituting for gasoline nationwide,[18] or improving an urban environment,[19] have been assessed. In the urban environmental study, it was shown for New York City, that a) hydrogen produced with off-peak power could supply over half of the expected 1985 energy needs for transportation, b) its cost could be as low as $0.04 per pound making it quite competitive with conventional fuels, and c) that 5,331 million pounds of pollutants would be emitted from gasoline powered 1985 vehicles as compared to 216 million pounds of emissions from those same vehicles if they were fueled with hydrogen.

Hydrogen possesses some unique physical and chemical properties which offer an advantage over conventional fuels and thus influences its substitutability. In the first place, its wide flammability limits make it an ideal motor fuel. (This was demonstrated under a no-load condition with our hydrogen engine, for example, where it was extremely difficult to get either too rich or too lean of a fuel mixture for the engine to burn. This feature could be used advantageously in the transition from fossil to hydrogen fuel if the latter is used to promote hydrocarbon fuel oxidation in the lean combustion region where the production of nitrogen oxides is least favored.) Next, its extreme volatility coupled with its flammability would make for much easier starting in cool climates. Thirdly, its ability to chemisorb with certain metals to form hydrides enables it to be conveniently stored at ambient pressure and temperature. Since the reaction is reversible, it can be released from this inactive state merely by the addition of heat. Much of the heat released by internal combustion engines could be stored if it were used thusly to release hydrogen. This energy could then be regained during the recharging of the hydride if desired.

Other characteristics of hydrogen which influence its substitutability are: 1) its light weight and high energy density which gives it desirable storage features of particular value in aircraft and space vehicles, 2) its high flame speed enabling the design against flame-out and hardware for control of the high frequency flame jets used in the engine design reported herein, 3) a low flame incandescence which significantly reduces radiation (accordingly affecting the overall engine temperature), 4) its clean burning offering an opportunity for prolonged operation without oil change or the design of true muffler systems rather than also transporting the emissions to a location where their toxicity is unimportant (the number of deaths resulting from accidental carbon monixide poisioning each year is considerable), and finally 5) its low activation energy which offers an opportunity for engine designs using glow ignition instead of costly and troublesome spark ignition.

Three additional time dependent factors which influence hydrogen's substitutability are its short and long-term availability, its relative safeness, and its cost. Currently, production facilities are limited with supplies primarily coming from hydrocarbons and being consumed in ore-reduction processes, chemical synthesis, and space exploration. Since hydrogen is essential in producing synthetic oil and gas from coal or oil shale, first priority for its increased production should be allocated to expanding our energy base. Furthermore, since the electrical generating facilities of the nation are hard-pressed to meet current demand, it does not appear that there will be any significant opportunity in the immediate future for the development of an excess hydrogen supply. The circumstances involved have been summarized by McKelvey and Singer:[20]

> "In the longer term, our biggest problem will be energy and the only hope for the continuation of civilization lies in the development of nuclear breeders and fusion to maintain an inexhaustible energy supply. Many economists and bureaucrats fail to understand that major scientific developments do not come about automatically in response to price increases. Unless the necessary research and development is done early enough we may be in real trouble."

Insofar as safety is concerned, liquid hydrogen has been compared on a relative basis as being as safe as methane and gasoline.[21] In this comparison, the negative aspects of hydrogen's wide flammable limits, low ignition energy and tendency to detonate in air when confined were thought to be balanced by its positive factors of low heat radiation, lack of smoke to cause asphyxiation, non-toxic vapors, unlikely detonation if spilled and rapid evaporation. It would appear that hydrogen stored in the solid (hydride) form at ambient conditions, instead of as a liquid, should be even less hazardous to work with, and correspondingly easier to design safe handling systems than for gasoline.

The relative cost of hydrogen versus gasoline favors hydrogen provided it is made on a large scale as is now done with gasoline. Three separate economic studies which support this contention are contained in references 22, 23, and 24. The economic incentives for conversion to hydrogen can be expected to continue to improve as the cost of gasoline increases which it must do if the price for crude oil is allowed to swing with the supply-demand situation. An imbalance of foreign trade brought about in part by this nation's oil import program will probably continue to build up economic deficits which further increases both the short and long-term economic outlook for hydrogen.

Hydrogen Vehicle Forecast

One black sheep which could easily be the technological-environmental scape goat is hydrogen. This relatively unappreciated element is foreseen to play the dominant role in a "hydrogen economy" era sometime in the future. Toward this aim Weinberg[25] in 1959 proposed that nuclear energy be used as the fuel of the future to power small scale mobile units with electrolytic hydrogen. Several years later, Lessing[26] claimed that hydrogen will be the master fuel of a new age providing first an energy source for engine (fuel cell) operation and subsequently electrical power directly from the atom via the process of controlled fusion. Hammond,[27] in discussing the concept of a nuclear reactor centered Agro-Industrial complex, assumed hydrogen would play an important role in producing ammonia and for reducing metal ores. Later Weinberg and Hammond[28] presented a very positive outlook for the prospects of cheap hydrogen.

Hydrogen's bid as a future fuel is clearly evident in the transportation sector where the demands for mobile power are flexibility and intermittent use. In the futuristic "electric economy," the energy used in any mobile power unit must have previously existed at some previous time in the form of electricity. With this in mind, an expansion of the definition of "electric auto" is proposed to include vehicles powered by batteries, fuel cells, and hydrogen fueled internal combustion engines, and turbines provided the fuel is or has been in the form of electricity at one time or another. According to this definition, a new breed of electric autos is visualized as including vehicles powered by hydrogen fueled internal combustion engines which require very little if any change in serviceability or mode of operation over their gasoline counterparts.

During the transition to hydrogen many modifications of present internal combustion engines will be made so that both fuels can be burned simultaneously. Also engines will be designed and built exclusively for hydrogen operation. The hydrogen fueled internal combustion engine is expected to power the first electric autos which receive wide acceptance because of the high degree of perfection of modern engines and their relatively low cost. Second and third generation electric autos will use electric motors along with a power supply. These may be either storage batteries or fuel cells.

Comparison of fuel cells and storage batteries immediately brings out a basic difference in their nature. Storage batteries are strictly limited in their energy storage capacity by the initial amount of reactants. For a given battery size only a predetermined amount of energy may be stored. A fuel cell on the other hand can convert an unlimited amount of energy, the cell of course being subject to wear out. It is known that the reliability of storage batteries and of fuel cells is roughly equivalent.

Electric autos using storage batteries will be used extensively. However, due to their weight and charge limitations, they will be used only in a specialized area--urban (short-range) transportation. This type of vehicle is therefore thought of as a second generation electric auto. Such a system would have a self-contained recharger relying only on a source of current, and could provide convenient, economical short-range transportation.

Ultimately a hydrogen-oxygen or hydrogen-air fuel cell will provide the motive power for the transportation sector.

Benefits in Conversion to Hydrogen Vehicles

More so than any other, this nation has fostered the development of a society whose per capita energy consumption can only be matched by the level of affluence offered to its citizens. Although no other society has known such opulence, the experi-

experiment has reached such proportions of acceptance that secondary effects such as environmental degradation are now of primary concern.

Rather than accepting prescribed levels of pollution as a corollary to the free enterprise system, it would appear our nation has a unique opportunity to lead in the molding of a society which maximizes the ratio of per capita energy consumption to per capita pollution. That is, if the level of affluence of a society (or its ability to use natural resources) can be measured by its per capita energy consumption, and its rate of misuse of natural resources by its per capita pollution, then it would seem desirable to its citizens to try to maximize the former while minimizing the latter. If such a direction could be accepted as a national goal, then it becomes clear in which areas legislation is needed and what the National Energy Policy currently under formulation, for example, should prescribe. If this nation does not enjoin leadership in preserving the environment or if it waits while the level of energy consumption rises in the rest of the world, then the secondary effects of pollution could become the primary concern of all humanity.

It is believed that acceptance of the concept of hydrogen fueled vehicles is one step toward avoiding such an eventuality. Once accepted, it could provide the stimulus for economic growth and national prosperity.

Problems Expected in Transition to Hydrogen Vehicles

The problems which must be solved before hydrogen fueled vehicles can be universally accepted are seen to be: a) the design and construction of adequate hydrogen production, handling, and distribution systems, b) the development of hardware necessary to efficiently store and utilize hydrogen as a fuel in vehicles, and c) overcoming the generally held but undeserved public attitude that hydrogen is too hazardous to use as a motor fuel. Sufficient work has already been done to demonstrate that viable solutions to these problems are already at hand.

Discussion

Some pertinent comparisons of a relatively conventional pollution-free hydrogen fueled vehicle with some unconventional power sources receiving prominent attention as presented by Danis[29] are:

1. "The hydrogen-oxygen fuel cell - fuel is the same and so is its source.

2. "The electric vehicle - in the hydrogen engine, the ultimate source of energy is the same as for charging batteries, but water is electrolyzed instead of battery chemicals being regenerated.

3. "The working fluid is steam plus air - so we would have, in effect, an internal combustion steam engine operating on the Otto cycle rather than an external combustion Rankine engine.

4. "In the global perspective, petroleum resources would shrink in importance, while nuclear energy resources would increase proportionately to meet needs of electricity for hydrogen production.

5. "Emissions are steam only, plus traces of nitric oxide formed perhaps during periods of peak power demand. This steam could form nimbus or cumulus clouds, return as rain where it could be electrolytically dissociated again.

6. "Catalysts are not required."

The fact that hydrogen will promote gasoline oxidation thus enabling combustion without misfire up to 20:1 air-fuel ratios could be utilized in the long term phasing out of gasoline and phasing in of hydrogen.

Conclusions

The conversion of vehicles from conventional fuels to hydrogen is forecast to fulfill a more viable long-range solution to the air pollution problem than any heretofore proposed. The prospects for development of a total energy system which produces hydrogen from an abundant natural resource, water, and replenishes this supply upon combustion in an engine whose emissions are almost pollution-free, appears to be a worthwhile effort to pursue.

REFERENCES

1. Erren and Campbell, "Hydrogen: A Commercial Fuel for Internal Combustion Engines and Other Purposes," Journal of the Institute of Fuel, June 1933, Vol. VI, pp. 277-290.

2. Lichty, L.C., Combustion Engine Processes, McGraw-Hill, N. Y. (1967), p. 4.

3. Heinze, Edwin P. A., "Hydrogen Engines for Off-Peak Power Utilization," Power, February 1933, pp. 90-2.

4. King, R.O. et. al. "The Hydrogen Engine and the Nuclear Theory of Ignition," Canadian Journal of Research, June 1948, Vol. 26, Section F, pp. 264-276.

5. Murray, R.G., and Schoeppel, R.J., "A Progress Report on the Development of OSU's Hydrogen-Burning Engine." Proceedings, Frontiers of Power Technology Conference, Oklahoma State University, Stillwater, Oklahoma (1969), p. 14.

6. U.S. Patent 3,572,297, "Hydrogen Fueled Internal Combustion Engine," (March 23, 1971).

7. Murray, R.G. and Schoeppel, R.J., "Emission and Performance Characteristics of an Air-Breathing Hydrogen-Fueled Internal Combustion Engine," Proceedings, 1971 Intersociety Energy Conversion Engineering Conference, Boston, Mass., Aug. 3-6, 1971, p. 38, SAE paper No. 719009.

8. Deen, J.L. and Schoeppel, R.J., "Hydrogen and the Electric Economy," Proceedings, Frontiers of Power Technology Conference, Oklahoma State University, Stillwater, Oklahoma, September 30-October 1, 1971, p. 10-1.

9. Schoeppel, R.J., and Sadiq, S., "The Role of the Power Industry in Supporting the Hydrogen Engine and Clean Air," Proceedings, Frontiers of Power Technology Conference, Stillwater, Oklahoma (October 15-16, 1970).

10. Schoeppel, R.J., and Murray, R.G., "The Development of Hydrogen Burning Engines." Proceedings, Frontiers of Power Technology Conference, Oklahoma State University (1968), p. 12.

11. "The Search for a Low-Emission Vehicle," Staff Report, Prepared for the Committee on Commerce, U.S. Senate, U.S. Government Printing Office, Washington (1969).

12. "Exhaust Emission Standards and Test Procedures," Federal Register, Part II, Vol. 36, No. 128 (July 2, 1971).

13. Mechanical Engineering, p. 66 (December 1971).

14. Schoeppel, R.J., "Design of a Total Energy Management System for the Abatement of Air Pollution," Technical Paper SPE 2877, Gas Industry Symposium, Society of Petroleum Engineers of AIME, Omaha, Nebraska, (May 21-22, 1970).

15. Murray, R.G., and Schoeppel, R.J., "A Reliable Solution to the Environmental Problem: The Hydrogen Engine," Paper 700608, presented at SAE/AIAA/ASME Reliability and Maintainability Conference, Detroit, (July 20-22, 1970).

16. Schoeppel, R.J. "Prospects for Reducing Pollution Through Improved Energy Conversion and Utilization Processes," submitted to Energy Section, United Nations (working paper for Conference on Human Environment, Stockholm, Sweden, Spring, 1972) June 1, 1971 (Restricted).

17. Witcofski, R.D., "Hydrogen Fueled Hypersonic Transports," presented at ACS Symposium on Non-Fossil Chemical Fuels, Boston, Mass. (April 9-14, 1972).

18. Schoeppel, R.J., and Sadiq, S. "The Role of the Power Industry in Supporting the Hydrogen Engine and Clean Air," Proceedings, Frontiers of Power Technology Conference, Stillwater, Oklahoma (October 15-16, 1970).

19. Winshe, W.E., Sheehan, T.V. and Hoffman, K.C., "Hydrogen--A Clean Fuel for Urban Areas," Preceedings, 1971 Intersociety Energy Conversion Engineering Conference, Boston, Mass. (August 3-6, 1971).

20. McKelvey, V.E. and Singer, S.F., "Conservation and the Minerals Industry--A Public Dilemma," Geotimes, p. 20 (Dec. 1971).

21. Becker, J.V. and Kirkham, F.S., "Hypersonic Transports," NASA ST-Set 292, Paper No. 25 (Dec. 4, 1971).

22. Johnson, J.E., "Economics of Large Scale Liquid Hydrogen Production," Presented at Cryogenic Engineering Conference, University of Colorado, Boulder, Colorado (June 13-15, 1966).

23. Hallett, N.C., "Study, Cost, and System Analysis of Liquid Hydrogen Production" NASA CR-73,226 (June 1968).

24. Costa, R.L. and Grimes, V.G., "Electrolysis as a Source of Hydrogen and Oxygen," Chemical Eng. Progress, Vol. 63, 56-8 (1967).

25. Wèinberg, A.M., "Energy as an Ultimate Raw Material or - Problems of Burning the Sea and Burning the Rocks," Physics Today, Nov. 1959, p. 18.

26. Lessing, L. "The Master Fuel of a New Age," Fortune, May, 1961, p. 152.

27. Hammond, R.P., "Low Cost Energy: A New Dimension," Science Journal, January, 1969.

28. Weinberg, A.M. and Hammond, R.P., "Limits to the Use of Energy," American Scientist, Vol. 58, P.412 (July-August, 1970).

29. Danis, L.J., "Trends in Piston Engine Combustion Chamber Components," Presented at ASM/AWS/AIME et al Westec Conference, Los Angeles (March 1971).